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Development and Characterization of PdCr Temperature-Compensated Wire Resistance Strain Gage

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Development and Characterization of PdCr Temperature-Compensated Wire Resistance Strain Gage

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Abstract

A temperature-compensated resistance static strain gage with potential to be used to 600°C was recently developed. Gages were fabricated from specially developed palladium-13w/o chromium (Pd-13Cr) wire and platinum (Pt) compensator. When bonded to high temperature Hastelloy X, the apparent strain from room temperature to 600°C was within 400 microstrain for gages with no preheat treatment and within 3500 microstrain for gages with 16 hours prestabilization at 640°C. The apparent strain versus temperature relationship of stabilized PdCr gages were repeatable with the reproducibility within 100 microstrain during three thermal cycles to 600°C and an 11 hours soak at 600°C. The gage fabrication, construction and installation will be described. Also, the coating system used for this compensated resistance strain gage will be explained. The electrical properties of the strain sensing element and main characteristics of the compensated gage including apparent strain, drift and reproducibility will be discussed.

Introduction

There has been a continuing interest and need for resistance strain gages which are capable of making static strain measurements in the hot structure of the gas turbine engines, e.g. combustor, turbine blades and vanes. Although the search for suitable materials for high temperature strain gages usage has been under way since the introduction of the wire resistance strain gage some 50 years ago, none of the strain gage system meets all of the desired characteristics at high temperatures. For example, all of the iron-chromium-aluminum systems, including Chinese 700°C and 800°C gages, Kanthal A-1 gages and BCL3 gages (ref.1-3) have some order-disorder transition in the temperature range of 400°C-500°C. Their apparent strain data show large cycle to cycle nonrepeatability and is strongly dependent on the heating and cooling rate of the previous cycle. Care is required in using these gages in the unstable temperature region. The commonly used HT-1200 platinum-tungsten alloy gage, with its high temperature coefficient of resistance (240 ppm/C) and internal oxidation, is also limited as a high temperature strain gage.

Recent work at NASA Lewis Research Center to develop a high temperature static strain gage systems has emphasized on a palladium-13w/o chromium (Pd13Cr) alloy. This alloy was developed under a contract with United Technologies Research Center. The Pd13Cr alloy in bulk form appears to have the desired characteristics such as having a linear, stable, repeatable resistance versus temperature relationship up to 1000°C (ref.4). The contract effort is continuing along with work at NASA Lewis Research Center with the objective of developing a thin film or fine wire high temperature static strain gage system. This paper will describe the progress of the PdCr wire static strain gage system.

Strain Sensing Material

Study of the Pd-13Cr alloy in bulk form (460 micrometer minimum sample thickness) revealed that this alloy was structurally stable. It has no phase transformation in the range of room temperature to 1000°C. It forms an adherent, self-protective scale of Cr_2O_3 at 1000°C in air which results in a repeatable, stable resistance versus temperature relationship which is independent of the heating- and cooling-rates (ref. 4). However, the oxidation protection scale was found to be thickness dependent. When the alloy was prepared as a 6.5 micrometer thick sputtered film, the Cr_2O_3 scale did not provide sufficient protection from oxidation.

Resistance drift at several temperatures of a 25 micrometer (1 mil) bare PdCr wire drawn in China was measured after fast cooling from 600°C to the test temperature at which it was held for 16 hours. These measurements were compared to measurements made on other strain sensing materials (data from reference 5) as shown in Fig. 1. The results show that 25 micrometer PdCr bare wire has the smallest resistance drift to about 480°C (900°F) among the gage materials tested. Its resistance drift at 480°C was 1090 ppm for 16 hours. At temperatures higher than 500°C, resistance drift of this wire becomes too large to be neglected. The use of an additional protective overcoating system is therefore necessary before this 25μm PdCr wire can be used at higher temperatures.

Oxidation protection for PdCr fine wires was tried by applying a high temperature cement coating on the wires. Fig. 2 shows the resistance

drift at 800°C of the 25 μm PdCr bare wire, wire coated with alumina base cement (Contronics 901 cement) and wire coated with mixture cement (Contronics 901 cement with 4 weight percent of Aremco 516 zirconia base high temperature cement). It can be seen that with alumina base cement on the PdCr wire decreased the resistance drift of PdCr at 800°C by a factor of 1.5. Addition of 4 wt% of zirconia base cement to the alumina base cement further decreased the resistance drift of PdCr by approximately an order of magnitude. A scanning electron microscope (SEM) and an energy dispersive spectrometer (EDS) were used to examine the wires after testing. The SEM micrographs and EDS spectrum for the wires with cement coating are shown in Fig. 3 and 4, respectively. Balls of palladium and depletion of chromium on the surface was found on the wire coated with alumina base cement alone but not on the wire coated with mixture cement.

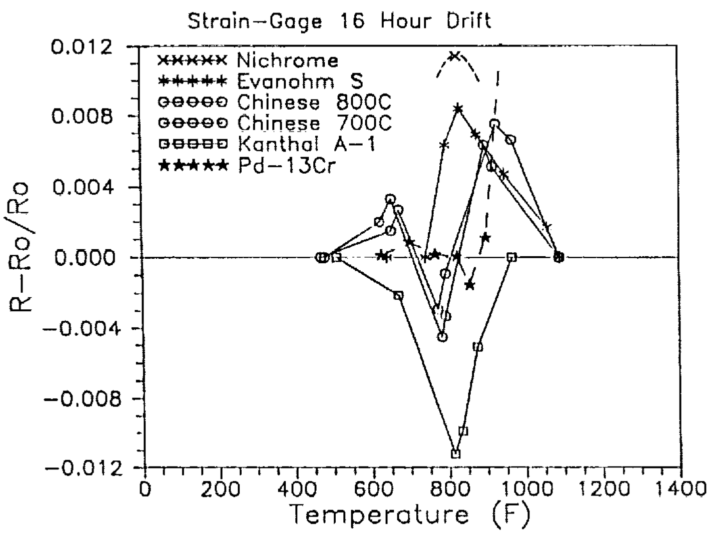

Fig. 1. Comparison the 16 hours resistance drift of 1 mil Pd13Cr with that of other strain sensing materials. (data from ref. 5)

Many researchers have found that addition of zirconia increases the oxidation protection capabilities of alumina The addition of rare earth elements to high temperature alloys has been shown to densify the oxide films, lower the diffusion of oxygen and therefore slow down the oxidization process and improve the adherence of oxide scales (ref. 6-7). The mechanism by which zirconia addition improves the oxidation resistance of PdCr is not yet understood. Further investigation is required to optimum the oxidation protection of PdCr by addition of zirconia or some other rare-earth element to the alumina coating.

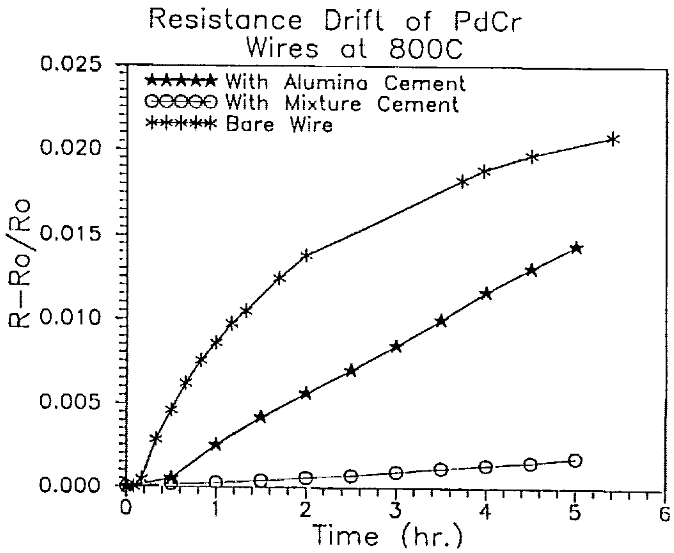

Fig. 2. Comparison the resistance drift at 800°C for PdCr bare wire, wire coated with alumina cement and wire coated with mixture cement.

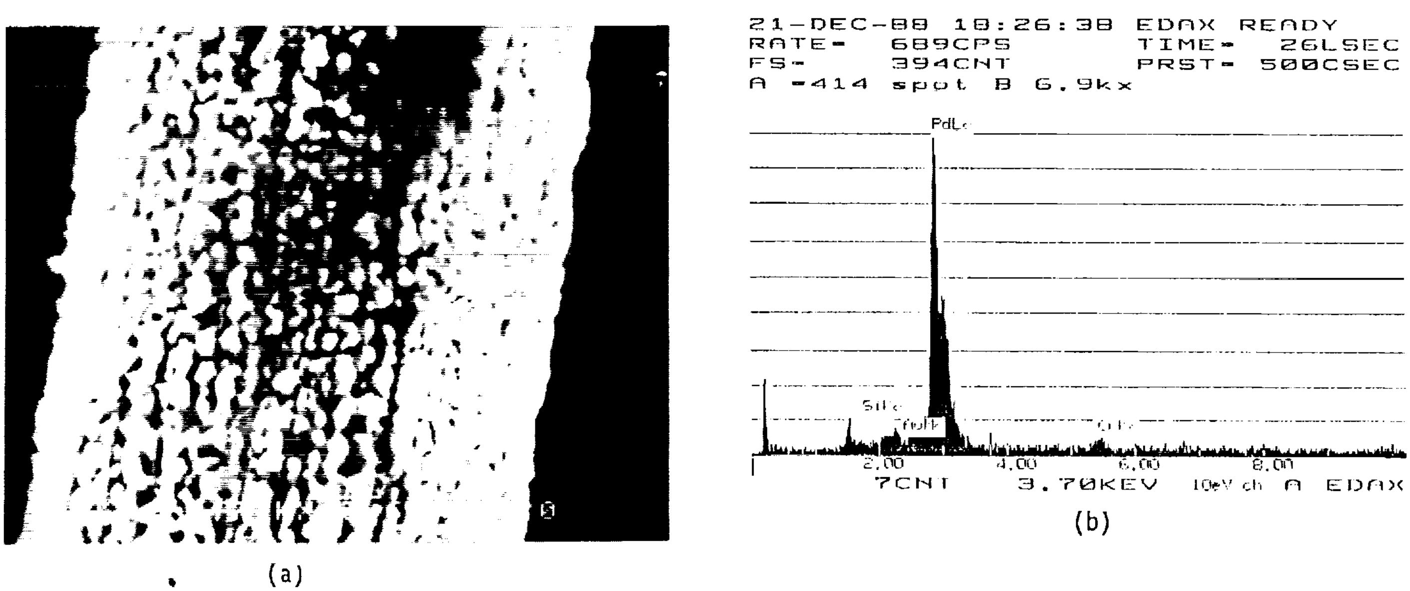

Fig. 3. (a) SEM micrograph (b) EDS spectrum of wire with alumina base coating after 16 hours thermal soak at 800°C.

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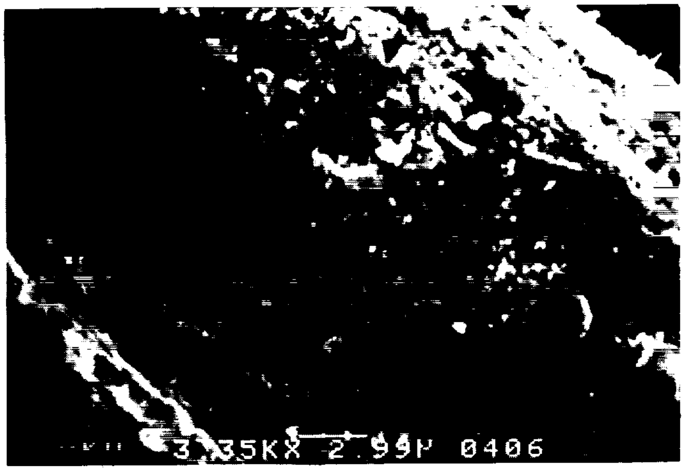
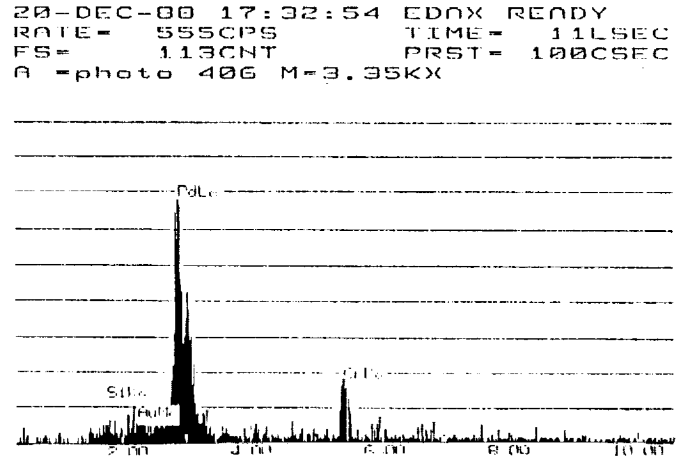


(a)



(b)

Fig. 4. (a) SEM micrograph (b) EDS spectrum of wire with mixture cement coating after 16 hours thermal soak at 800°C.

The resistance changes with temperature to 600°C for PdCr 25μm bare wire and wire coated with mixture cement are shown in Fig. 5 and 6, respectively. Notice that resistance value of bare PdCr at certain temperature changed slightly from cycle to cycle (Fig.5). The resistance decreased about 0.7% and temperature coefficient of resistance (TCR) increased about 6.9% after a cycle to 600°C. This corresponded to approximately a loss of 1% of chromium. The resistance stability and reproducibility of PdCr certainly improved by coating the wire with mixture cement. The repeatability between cycles was preserved even after a 15 hour thermal soak at 600°C (Fig.6).

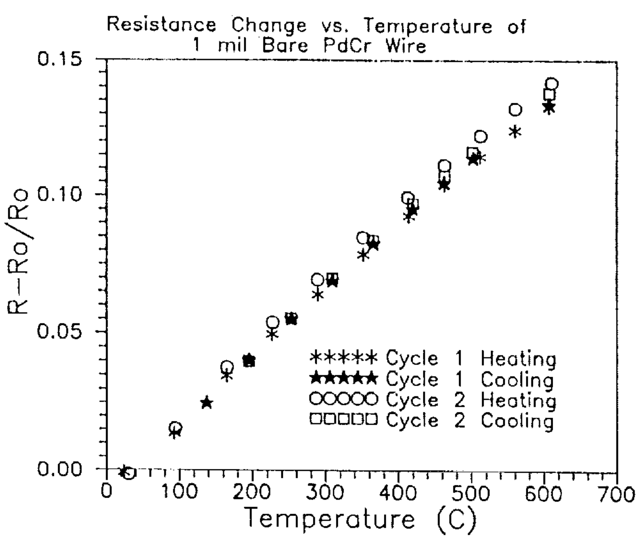


Fig. 5. Resistance change with temperature of 1 mil bare PdCr wire during two thermal cycles to 600°C.

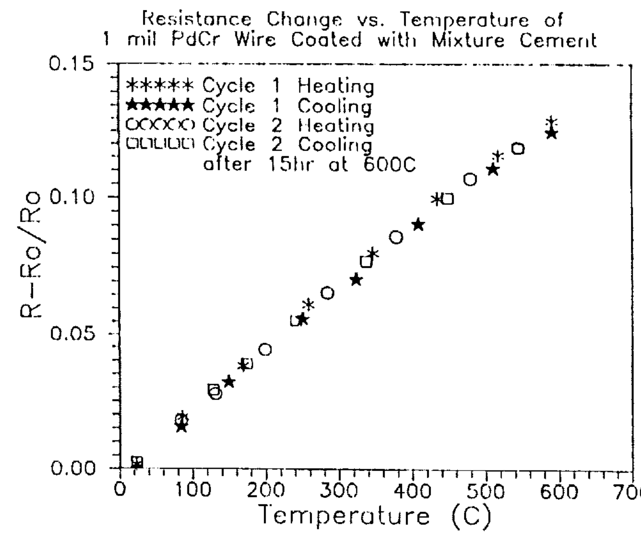


Fig. 6. Resistance change with temperature of PdCr wire coated with mixture cement during two cycles to 600°C and a 15 hours thermal soak at 600°C.

Construction and Fabrication of Gages

Due to the fact that Pd-13Cr has a fairly high temperature coefficient of resistance (175 ppm/C), a temperature compensation system is required for using it as a strain sensing material.

The compensated PdCr strain gages developed were fabricated from 45 μm diameter PdCr wire drawn at Battelle-Columbus laboratories. The size of the strain gage grid is 8.2 mm long and 10.6 mm wide and the nominal resistance is 81 ohm. The compensating resistor is platinum wire 25 μm in diameter. The compensator grid is 4.2 mm long and 12.6 mm wide and has a nominal resistance of 10.1 ohm. The configuration of the compensated strain gage is shown in Fig.7. The leads are also PdCr wire but are 75 μm in diameter. These leads are spot welded to the gage wires.

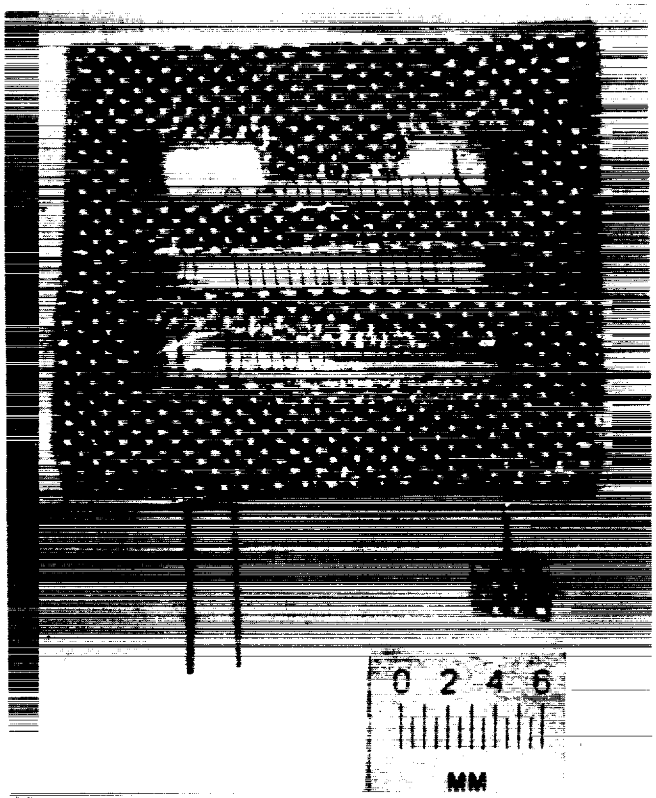


Fig. 7. The configuration of temperature compensated PdCr wire strain gage.

The PdCr compensated wire gages were wound and mounted on the Hastelloy X test coupons at NASA Lewis Research Center. There was one gage on each side of the coupon. Mixture cement, which was made of Contronics 901 alumina base cement with 4 weight percent of Aremco 516 zirconia base cement, was used both for electrical insulation under the strain gages and for an oxidation protection overcoat. The cement should be thick enough to have sufficient resistance to ground but thin enough to minimize thermal cracking. The bonded gage shown in Fig. 8 was cured at room temperature for 4 hours, followed by oven drying at 93°C for 2 hours, then fired from 121°C to 371°C in one hour.

On each side of the Hastelloy X substrate there were also two thermocouples spot-welded to the plate to monitor the temperature of the gages and to detect the temperature gradient across the plate. During the tests, the temperature difference from top to bottom and from side to side of the test plate was found to be less than 2°C.

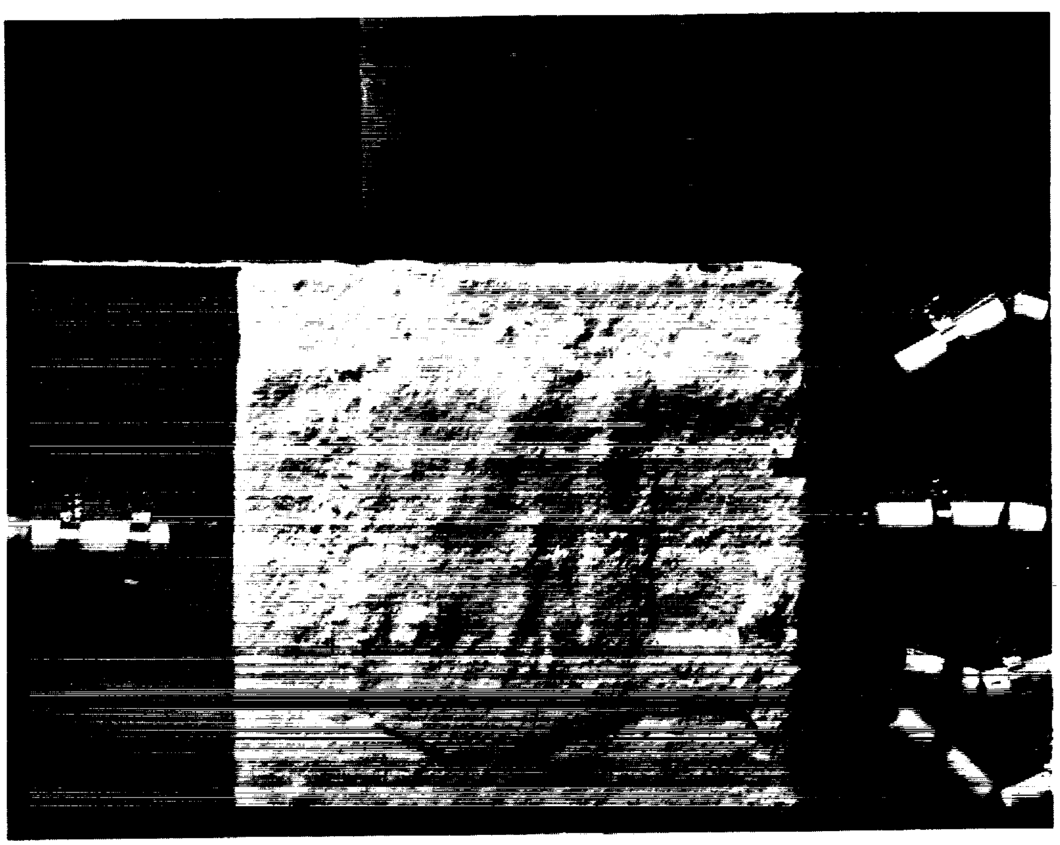


Fig. 8. PdCr strain gage on Hastelloy X-plate. Gage were coated and installed with mixture cement. Two thermocouples were spot-welded on the plate.

Temperature Compensation Technique

The temperature compensation circuit, technique, and some considerations related to the technique are discussed in the reference 8. The gage and compensating element are connected to adjacent arms of a Wheatstone bridge circuit. In this configuration the compensator will minimize the effect of temperature change upon the resistance of the gage. The bridge balance will be responsive only to the mechanical strain imposed on the active gage.

All the tests were conducted in air and included apparent strain testing during several temperature cycles and gage drift at high temperatures with no load. Gage factor tests at room temperature and at several high temperatures as well as several strain levels will be conducted in the near future. The strain gage lab is automated to provide computer control of oven temperatures, imposed strain and data sampling. This system is described in the reference 9.

Results and Discussion

The compensated bridge was set up based on the measured resistance and temperature coefficients of resistance of PdCr gage and Pt compensator. With the bridge balanced at room temperature, thermal outputs were measured from room temperature to 600°C. Fig. 9 and 10 show the resulting apparent strain for the gage without any preheat treatment and for the gage after being prestabilized at 640°C for 16 hours. It is seen that the apparent strain over the temperature range to 600°C was within 400 microstrain for gages with no heat treatment, and was within 3500 microstrain for the stabilized gages. The apparent strain for the uncompensated PdCr strain gage would have been approximately 65000 microstrain in the same temperature range. Values of apparent strain were calculated assuming a gage factor is 2. The leakage resistance to ground was above 20 Megohms at all temperatures.

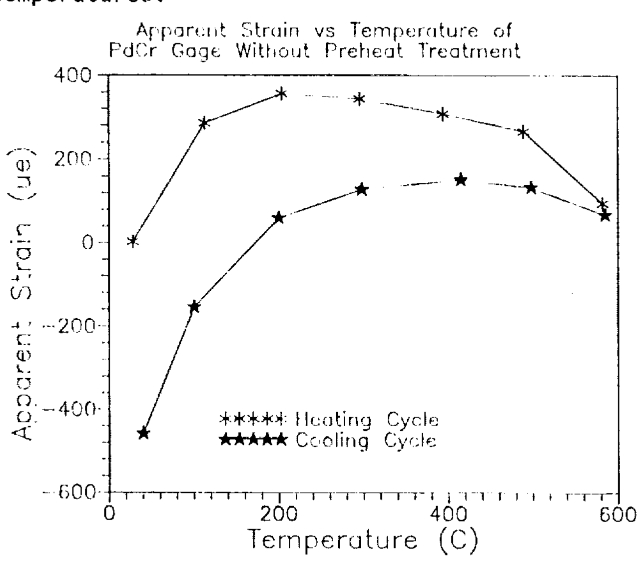


Fig. 9. The apparent strain versus temperature of coated PdCr gage with no preheat treatment.

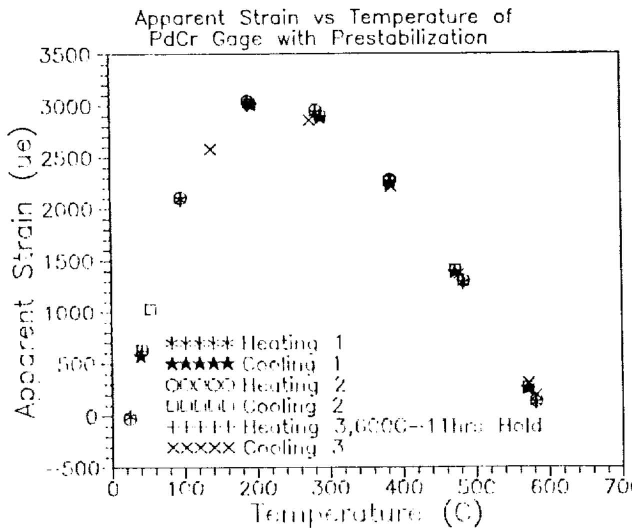


Fig. 10. The apparent strain versus temperature of PdCr gage after being prestabilized at 640°C for 16 hours. Gage were coated with mixture cement.

The resistance drift at 600°C was very small for the stabilized gages. The reproducibility of apparent strain with temperature between thermal cycles were within 100 microstrain even after an 11 hour thermal soak at 600°C, as shown in Fig. 11. The sigma deviation of all the apparent strain data points from the curve drawn through the average of the data points at each test temperature was about 26 microstrain over the temperature range. Note that the bridge was not rebalanced to zero between cycles. The reproducibility of apparent strain and drift of the PdCr gages was improved by prestabilized the gages.

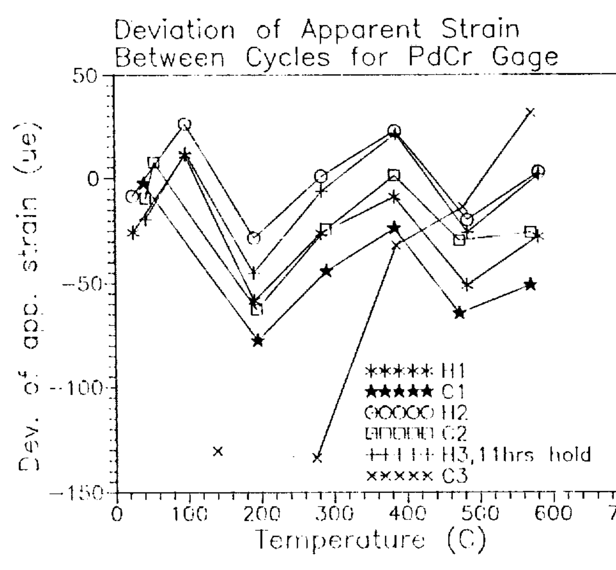


Fig. 11. The deviation of apparent strain between 3 cycles of heating and cooling to 600°C and a 11 hours thermal soak at 600°C.

Care should be taken during the prestabilization process, owing to the fact that oxidation of PdCr occurs at high temperatures, which results in changing the contents of chromium. Hence, the resistance and the thermal coefficient of resistance of PdCr as well as the linearity of the resistance versus temperature relationship are altered. The higher the temperature and the longer the time of the prestabilization process, the more the alteration occurs. The optimum prestabilization process for PdCr compensated strain gages is being characterized in order to get the best thermal output characteristic.

The cemented gages delaminated from the Hastelloy X substrate after six cycles to 600°C and a 27 hour thermal soak at 600°C. Poor adherence between cement and substrate may be due to the oxidation of the Hastelloy X substrate or the difference in thermal coefficient of expansion between that of the substrate and the basecoat cement. Adherence can be improved by a graded coating system in which a second layer provides a transition, in terms of thermal coefficient of expansion, between the Hastelloy X and alumina cement.

Preliminary apparent strain cycle tests to 700°C were also taken despite the fact that gages had been partially detached from the plate just to get an idea of the gage behavior at 700°C. The results are shown in Fig. 12. It can be seen that the apparent strain versus temperature curves follow the same track as that of the 600°C cycle tests. The apparent strain from room temperature to 700°C was within 4000 microstrain. However drift in resistance of the gages was noticeable at 700°C, and the reproducibility of apparent strain with temperature between thermal cycles to 700°C was not as good as that of the 600°C cycle tests.

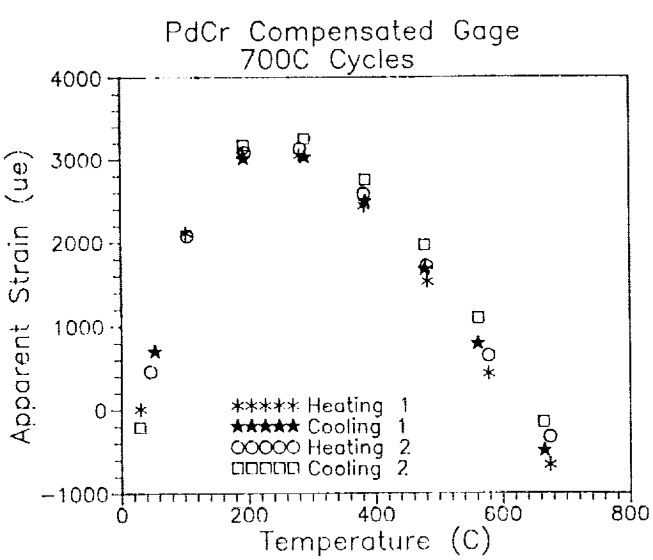


Fig. 12. Preliminary results of apparent strain versus temperature test of PdCr compensated gage during 2 thermal cycles to 700°C.

Oxidation protection of the compensated PdCr strain gages tested was not good enough mainly due to the poor adherence of basecoat to the Hastelloy X alloy. The temperature coefficient of resistance of the gage itself increased and resistance decreased after cycling. This indicated the loss of chromium. The linearity of the resistance versus temperature relationship also altered, which results in higher values of apparent strain than expected. Development of the resistance static strain gages to be used above 600°C is continuing at NASA Lewis.

Conclusions

1. A special Pd-13w/oCr temperature compensated wire strain gage has been tested over a temperature range to 700°C. The thermal output from room temperature to 600°C was less than 400 microstrain for gages without any heat treatment and within 3500 microstrain after gages being stabilized at 640°C for 16 hours. The apparent strain from room temperature to 700°C of the stabilized gages was within 4000 microstrain.

2. An addition of small amounts of zirconia to the alumina cement coating attributed good oxidation protection to the PdCr gage system. The effects of amount of zirconia and other rare earth oxide addition (e.g. Y_2O_3, HfO) on the oxidation protection of PdCr gage system are being studied.

3. The resistance versus temperature curve of PdCr tends to be stable after prestabilization at 640°C for 16 hours. This can be done in an air furnace. However, the optimum procedure of prestabilization for PdCr wire strain gage is still under investigation.

4. The apparent strain versus temperature relationship of coated and stabilized PdCr gages were repeatable between cycles. The reproducibility of apparent strain with temperature between cycles were within 100 microstrain even after an 11 hour thermal soak at 600°C. PdCr compensated wire strain gage provides the best apparent strain repeatability between thermal cycles among the existing gages used over this temperature range.

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16. Abstract

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